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Improvements to colour film projection by modifying the spectrum of the illumination

No. 1970/19

Research Department, Engineering Division
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(PH-60)

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IMPROVEMENTS TO COLOUR FILM PROJECTION BY MODIFYING THE SPECTRUM OF THE ILLUMINATION

SUMMARY

A theoretical investigation has been carried out into the possibility of improving the quality of reproduction of colour film by the use of a modified form of projection illuminant. A simplified treatment has been followed which neglects the effects of masking in the photographic process and assumes an overall gamma of unity for the photographic process. Significant improvements in the chromaticity of displayed colours are obtained by the use of an illuminant which reduces the effect of cross-coupling between the film dyes. Depending on the particular colour, however, the luminance may be either slightly improved or moderately impaired by the use of such an illuminant. A small but significant improvement in colour rendering is achieved.*

1. INTRODUCTION

The reproduction of scenes by colour film relies on the subtractive principle of colour mixing. In the ideal case the blue, green and red parts of the illuminant are controlled and modified separately by the appropriate dyes of the positive print and the transmitted light is then allowed to fall on to a screen. A yellow dye controls the blue, a magenta dye the green, and a cyan dye the red part of the spectrum. Unfortunately no real dyes exist which are able to control only a limited part of the spectrum and the absorption curves of the best available dyes overlap to a considerable extent. This fact partly accounts for the inability of colour film to reproduce saturated colours at high relative luminance. For example, a saturated blue requires that maximum amounts of magenta and cyan dyes be present and the unwanted absorptions of these dyes in the blue region must reduce the overall luminance of the combination.

The unwanted absorptions of the three dyes in regions where they are supposed to be non-absorbing may be considered as cross-talk between wanted and unwanted modulation of light of a particular wavelength. The effect of this cross-talk is greatest in the two spectral regions near the cross-over points of the characteristic dye spectral-density curves, since here each dye has approximately an equal effect on the illuminant and the ratio of wanted to unwanted modulation is near unity. If, however, the illuminant energy is removed from these regions, the effect of the cross-talk may be greatly reduced.** In the limit, as these gaps in the spectrum are extended, this amounts to using three almost monochromatic sources whose intensities are controlled by the amounts of the three dyes present. However, theory shows that the original negative film analysis curves are then incorrect, since they do not apply to projection using three almost monochromatic sources.

A modified projection illuminant could also give a white point corresponding to Illuminant D_{6500}, the white point of a colour monitor display, instead of 5400°K, the more usual colour temperature of a projection illuminant. Because of the reduction in cross talk and the adjustment of the white point, optically projected film would then bear a closer resemblance to a television display, and this could well be of value in previewing film for television.

The present investigation has been undertaken to find out whether an illuminant can be postulated which fulfils these two requirements.

2. THEORETICAL PRINCIPLES

The theory of subtractive colour reproduction processes is most easily understood by assuming simplified forms for the positive-dye spectral characteristics. These usually take the form of block dyes, each of which has a rectangular absorption characteristic over one of the three portions of the spectrum (red, green and blue) and may have unwanted

* The term 'illuminant' refers to the spectrum (relative power per unit wavelength range) of the illuminating source, without regard to its absolute intensity

** This idea was originally proposed by Messrs. G.D. Monteath and C.B.B. Wood.

uniform absorptions over the other two. Of great importance is the derivation of the colour reproduction equations relating the concentrations (or densities) of the positive dyes to the corresponding exposures of the negative.

The relative exposures R, G and B forming the latent images in the negative film, are defined[1] by

$$\left.\begin{aligned} R &= \frac{\int f_r(\lambda)\, i(\lambda)\, r(\lambda)\, d\lambda}{\int f_r(\lambda)\, i(\lambda)\, d\lambda} \\ G &= \frac{\int f_g(\lambda)\, i(\lambda)\, r(\lambda)\, d\lambda}{\int f_g(\lambda)\, i(\lambda)\, d\lambda} \\ B &= \frac{\int f_b(\lambda)\, i(\lambda)\, r(\lambda)\, d\lambda}{\int f_b(\lambda)\, i(\lambda)\, d\lambda} \end{aligned}\right\} \qquad (1)$$

where $f_r(\lambda)$, $f_g(\lambda)$ and $f_b(\lambda)$ are the negative film analysis curves, $i(\lambda)$ is the object illuminant and $r(\lambda)$ is the object spectral transmittance or reflectance. Exposure densities[2] may also be defined by

$$\left.\begin{aligned} D_r &= -\log_{10}R \\ D_g &= -\log_{10}G \\ D_b &= -\log_{10}B \end{aligned}\right\} \qquad (2)$$

The positive-dye characteristics are usually quoted in the form of density curves $d_r(\lambda)$, $d_g(\lambda)$ and $d_b(\lambda)$ such that the combination $d_r(\lambda) + d_g(\lambda) + d_b(\lambda)$ results in a neutral with a certain density, say D_o, when viewed using a stated illuminant. Each dye density curve when specified in the above way is said to have an equivalent neutral density (e.n.d.) equal to D_o and an equivalent neutral transmission equal to T_o where $T_o = 10^{-D_o}$.

Theory shows[3] that for the case of ideal block dyes without unwanted absorptions the equivalent neutral densities of the three positive dyes should, for exact colour reproduction, be equal, respectively, to the exposure densities D_r, D_g and D_b. For the case of ideal block dyes with unwanted absorptions the three equivalent neutral densities should each be linear combinations of the three exposure densities; the equations defining the equivalent neutral densities are then known as masking equations. For the case of real dyes the relationships between the equivalent neutral densities and the exposure densities cannot be expressed simply.[2] Nevertheless, as a first approximation, the simple relationships for block dyes without unwanted absorptions can be expected to yield useful information when used with real dyes.

If the equivalent neutral densities of the positive dyes are therefore assumed to be D_r, D_g and D_b, the characteristic dye density curves, $d_r(\lambda)$, $d_g(\lambda)$ and $d_b(\lambda)$ must be multiplied by factors D_r/D_o, D_g/D_o and D_b/D_o in order to obtain the positive-film spectral density $d(\lambda)$ (the sum of the three separate densities neglecting interface effects) corresponding to the relative exposures R, G and B.

Hence

$$d(\lambda) = \left[D_r d_r(\lambda) + D_g d_g(\lambda) + D_b d_b(\lambda)\right]/D_o$$

$$= -\left[d_r(\lambda)\log_{10}R + d_g(\lambda)\log_{10}G + d_b(\lambda)\log_{10}B\right]/D_o$$

using equations (2)

$$= -\log_{10}\left[R^{d_r(\lambda)/D_o} \,.\, G^{d_g(\lambda)/D_o} \,.\, B^{d_b(\lambda)/D_o}\right] \qquad (3)$$

The positive-film spectral transmission, $t(\lambda)$ is given by $t(\lambda) = 10^{-d(\lambda)}$

$$= R^{d_r(\lambda)/D_o} \,.\, G^{d_g(\lambda)/D_o} \,.\, B^{d_b(\lambda)/D_o} \qquad (4)$$

For example, a grey of uniform spectral reflectance T gives

$$R = G = B = T$$

and $$t(\lambda) = T^{\left[d_r(\lambda) + d_g(\lambda) + d_b(\lambda)\right]/D_o} \qquad (5)$$

Thus, if the positive dyes were block dyes the function $d_r(\lambda) + d_g(\lambda) + d_b(\lambda)$ would be equal to D_o throughout the spectrum and consequently the positive-film spectral transmission would be equal to T. In practice the function varies about the value D_o and gives the spectral transmission $t(\lambda)$ a corresponding variation about the value T. For the case of $T = 10^{-D_o}$ the spectral transmission nevertheless, appears exactly neutral when viewed with the correct illuminant, by virtue of the definition of the e.n.d. For any other value of T the spectral density $d(\lambda)$ is simply multiplied by a different scale factor but the spectral transmission $t(\lambda)$, being exponentially related to $d(\lambda)$, is not simply multiplied and its appearance may deviate slightly from exact neutrality.

Equations (1) and (4) enable the positive-film spectral transmission to be calculated when the negative is exposed to any object of known spectral reflectance provided that the negative-film analysis curves, the positive-print spectral densities and the object illuminant are known. A knowledge of the projection illuminant, $e(\lambda)$, enables the trichromatic coefficients (x, y) and relative luminance (l) for the illuminant-plus-film combination to be deduced as follows:

$$\left.\begin{aligned} X &= \int e(\lambda)t(\lambda)\bar{x}(\lambda)d\lambda \\ Y &= \int e(\lambda)t(\lambda)\bar{y}(\lambda)d\lambda \\ Z &= \int e(\lambda)t(\lambda)\bar{z}(\lambda)d\lambda \\ x &= X/(X+Y+Z) \\ y &= Y/(X+Y+Z) \\ l &= Y/\int e(\lambda)\bar{y}(\lambda)d\lambda \end{aligned}\right\} \qquad (6)$$

where X, Y and Z are the tristimulus values of the combination and $\bar{x}$, $\bar{y}$ and $\bar{z}$ are the spectral tristimulus values (based on the C.I.E. primaries).

The x and y values may then be transformed to the u and v values on the uniform chromaticity diagram, and the values u, v and l may be termed the display co-ordinates.

Strictly, the projection illuminant, $e(\lambda)$, should be that specified in the positive dye-density characteristics since the equivalent neutral density D_o is referred to this illuminant. If any other illuminant is used the three dye-density curves should be weighted slightly differently, so as to produce a visual neutral density of value D_o, before being used in equation (3). In practice, the omission of this procedure results in only small errors if the colour temperature of the illuminant is close to that of the specified illuminant and neither has any high-energy spectral lines.

Since colour film reproduction is essentially trichromatic, it relies on metameric matching. Specifically, if the reproduction is exact, the displayed colour is a metameric match to the original colour when illuminated with the same illuminant. In general, the reproduction will not be exact and the actual or practical display co-ordinates will differ from the ideal co-ordinates deduced from knowledge of the original colour and the projection illuminant. If the negative film is exposed to several different colours the corresponding ideal and practical display co-ordinates may be deduced using equations (1), (4) and (6) and the pattern of errors will show which colours the film is unable to reproduce satisfactorily within a chosen colour gamut.

If the projection illuminant spectrum is now modified the actual display co-ordinates will, in general, change and also the colour errors will change. It is desirable that the modification be such that the modified spectrum gives a metameric match to the unmodified spectrum so that the white point of the display remains the same, and thus the ideal display co-ordinates may justifiably be referred to the unmodified spectrum. Clearly, the modification will be beneficial if the errors in the displayed co-ordinates of a representative selection of colours decrease. It may be, however, that some errors decrease at the expense of others and it then becomes necessary to take a weighted mean of the errors. When, for some particular illuminant, this weighted mean has a minimum value, the projection illuminant can be taken to be optimized although there is no guarantee that a unique optimized spectrum exists.

3. PRACTICAL DETAILS AND RESULTS

The results fall conveniently into three stages: Positive-Film Spectral Transmission; Display Co-ordinates for Unmodified Illuminants; Illuminant Optimization.

3.1. Positive-Film Spectral Transmission

The positive-film spectral transmission was calculated using a computer programme based on equations (1) and (4). Analysis curves for Eastman 5251 negative film and dye spectral-density curves for Eastman 5385 positive film were used for the functions $f_r(\lambda)$, $f_g(\lambda)$, $f_b(\lambda)$ and $d_r(\lambda)$, $d_g(\lambda)$, $d_b(\lambda)$ respectively, and the positive-dye characteristics were referred to an e.n.d. of unity under Suprex Arc illumination. Object illuminants of E_{3000} and D_{6500} were used to discover the degree of dependence of the relative exposures R, G and B on the object illuminant. The integrations of equation (1) were performed as summations for 40 ordinates at 10 nm intervals in the range 380 to 770 nm and the positive-film transmission was likewise calculated at 10 nm intervals over the same range.

A grey scale in the form of steps of uniform spectral reflectance was first used for $r(\lambda)$. The resulting positive-film transmission curves, which must be identical for both object illuminants by consideration of equations (1) and (5), are shown in Fig. 1.

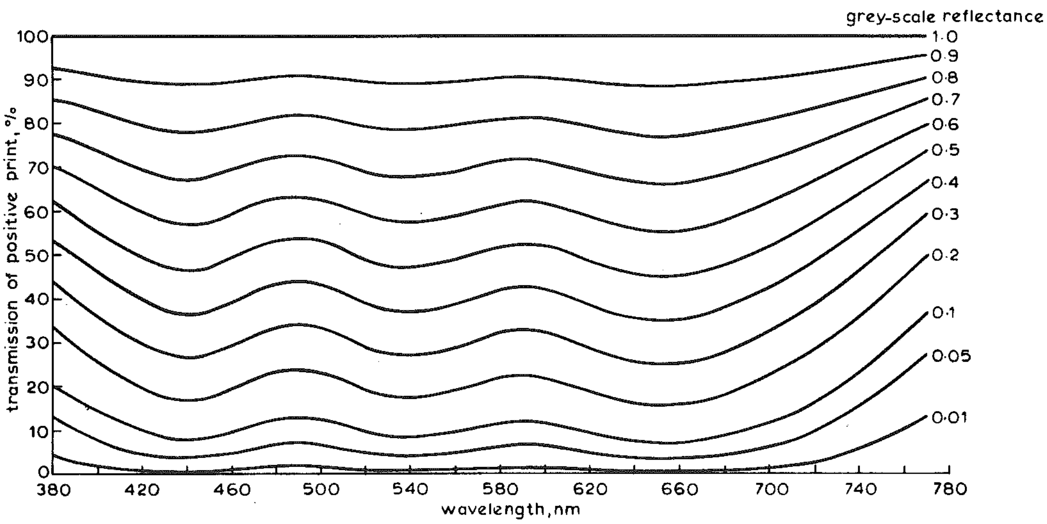


Fig. 1
Film spectral transmission for exposure to grey scale

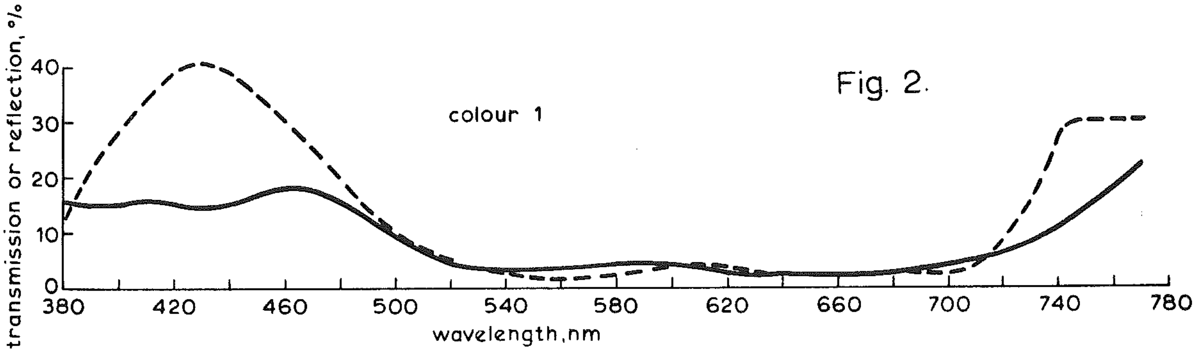


Fig. 2.

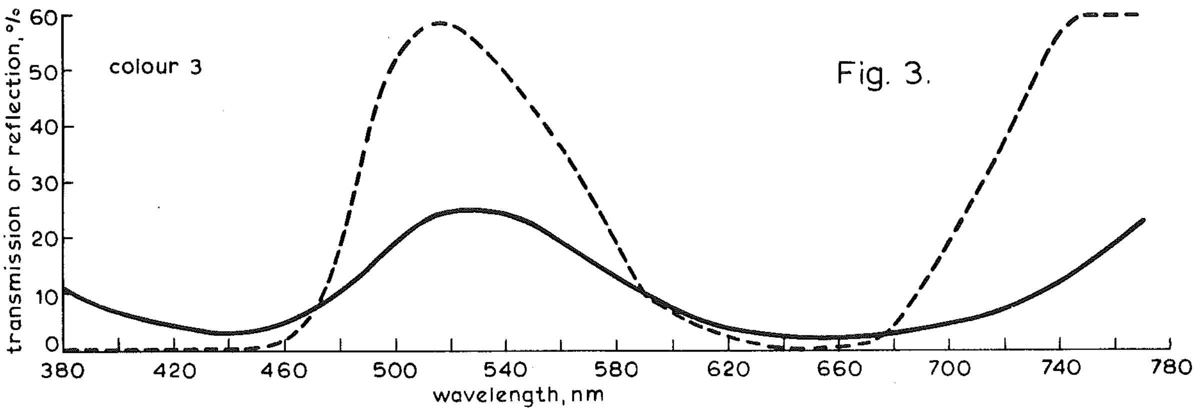


Fig. 3.

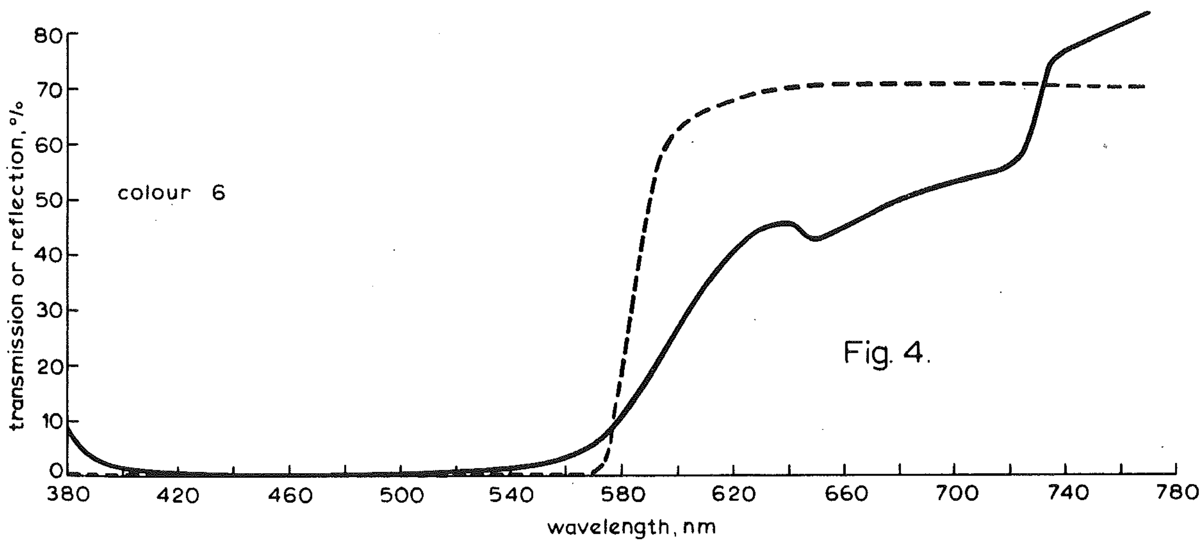


Fig. 4.

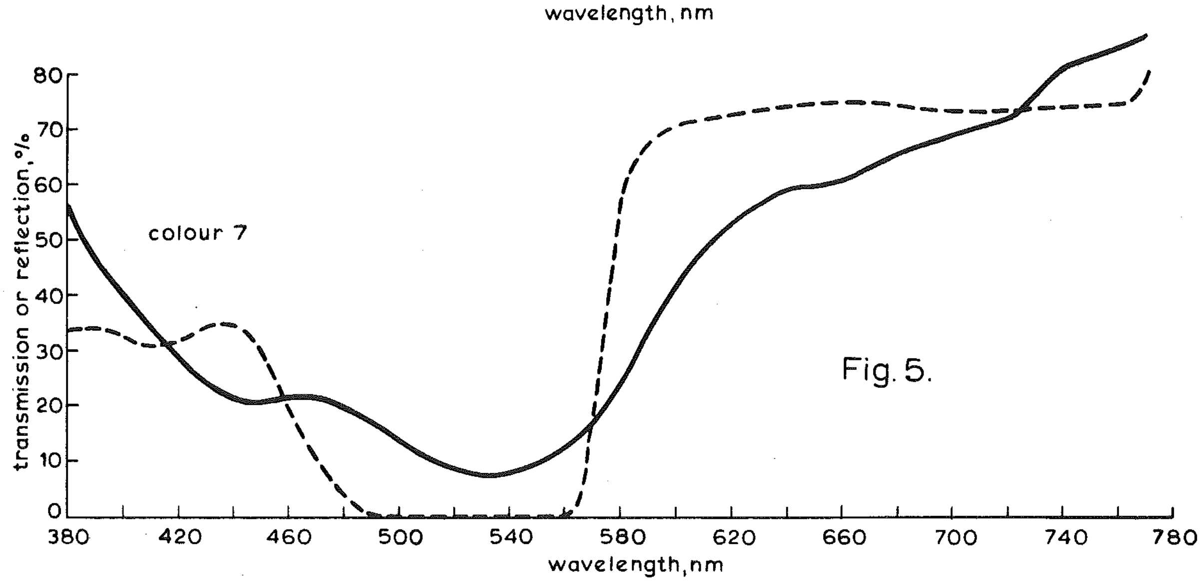
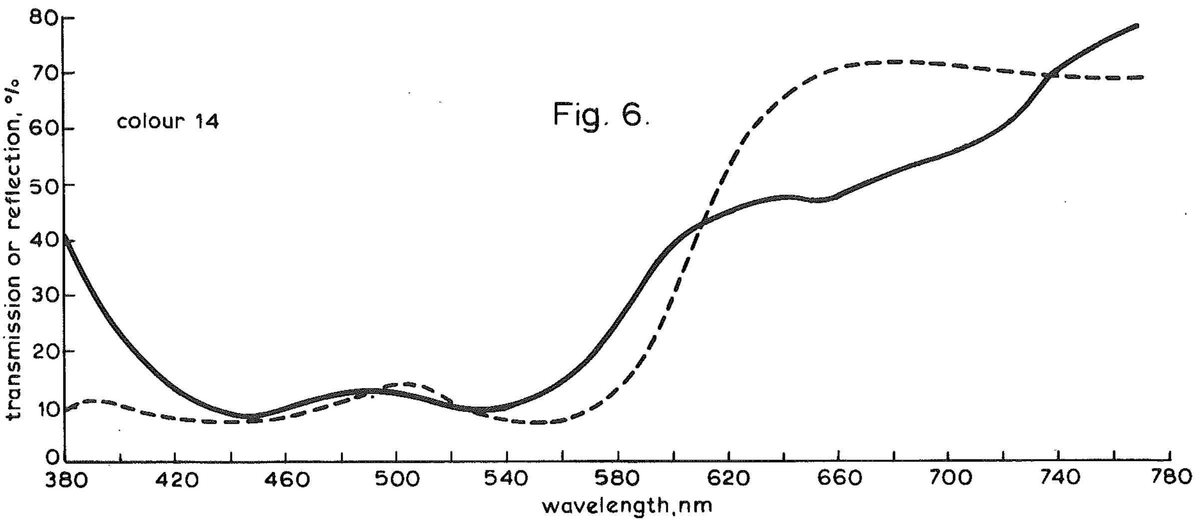
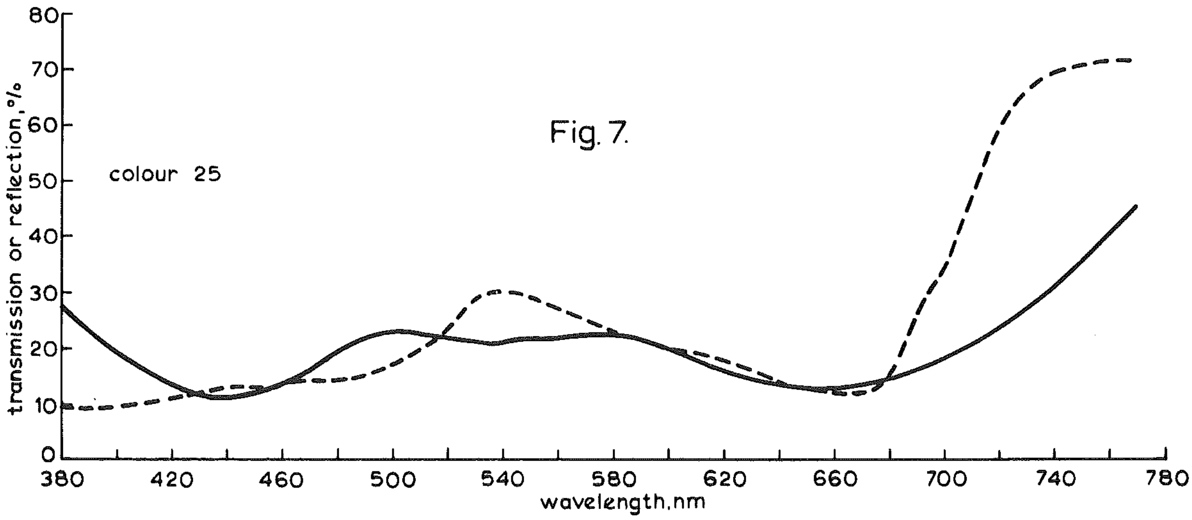


Fig. 5.





Figs. 2 to 7 - Film spectral transmission and object spectral reflectance for various test colours. Object illuminant D_{6500}

Twenty-six test colours, chosen to give a wide range of chromaticities, were then used for $r(\lambda)$; the set included eight saturated colours, eight desaturated colours, eight skin tones and two grass colours. In the case of saturated colours it was found necessary to impose an e.n.d. limit of four on the densities of positive dyes. The reason for this may be appreciated by consideration of equations (1) and (4); for saturated colours one of the relative exposures R, G or B may well be zero if the negative-film analysis and object spectral reflectance curves do not overlap. Zero exposure corresponds to infinite density, which never occurs in any practical film dye, but a limiting density of four is for almost all practical purposes equivalent to it.

The positive-film transmission curves obtained for each colour were relatively unaffected by choice of object illuminant and examples of the results obtained for the case of D_{6500} are shown by the solid lines in Figs. 2 to 7; the object reflectance curves are shown dotted. The particular results shown are those where the discrepancies between positive-film transmission and object reflectance were greatest.

3.2. Display Co-ordinates for Unmodified Illuminants

The computer programme of Section 3.1. was enlarged to include calculation of the display co-ordinates and errors of the projected colours, based on the uniform chromaticity scale (1960 C.I.E.). The chromaticity errors were expressed in j.n.d. units defined by

$$\Delta c = \left[(u_p - u_i)^2 + (v_p - v_i)^2\right]^{1/2} / 0{\cdot}00384$$

where Δc = chromaticity error in j.n.d. units

u_p, v_p = chromaticity co-ordinates of reproduction

u_i, v_i = chromaticity co-ordinates of original object

The luminance errors were expressed in j.n.d. units defined by

$$\Delta l = (\log_e l_p - \log_e l_i) / 0{\cdot}0198$$

where Δl = luminance error in j.n.d. units
l_p = luminance of reproduction
l_i = luminance of original object

The chromaticity co-ordinates of the colours actually displayed and the corresponding ideal values were plotted on the 1960 C.I.E.-U.C.S. diagram with the luminance errors beside the corresponding actual display co-ordinates. Finally, mean chromaticity (M_c), mean luminance (M_l) and overall errors were calculated, respectively defined as

$$M_c = (\Sigma\, \Delta c)/N,$$
$$M_l = (\Sigma\, \Delta l)/N,$$
$$M_o = \sqrt{M_c^{\,2} + M_l^{\,2}}$$

where N = number of test colours

A projection illuminant of D_{6500} was first assumed, i.e. that of a colour monitor display. In the case of the grey scale the chromaticity error increased monotonically from zero to 0·4 j.n.d. units and the luminance error from zero to 0·7 j.n.d. units as the grey reflectance decreased from 100% to 1%. The change in chromaticity of the projected grey scale was a result of the effects discussed in Section 2.

The chromaticity error for a 10% reflectance (unity e.n.d.) was a consequence of using D_{6500} instead of Suprex Arc for the projection illuminant.

The chromaticities and errors for the test colours are shown in Fig. 8. A general desaturation is apparent which is worst for the saturated colours where dominant-wavelength changes also take place. The luminance errors are also greatest for the saturated colours, as would be expected. The various mean errors, taken over all the colours, are shown in the first row of Table 1.

The display co-ordinates and errors were then calculated for a projection illuminant consisting of a black-body radiator at a temperature of 5400°K, the more usual condition in film projection. The results for the test colours are shown in Fig. 9. The general appearance is very similar to Fig. 8 except that the ideal chromaticity co-ordinates are shifted slightly. The average errors are given in row 2 of Table 1.

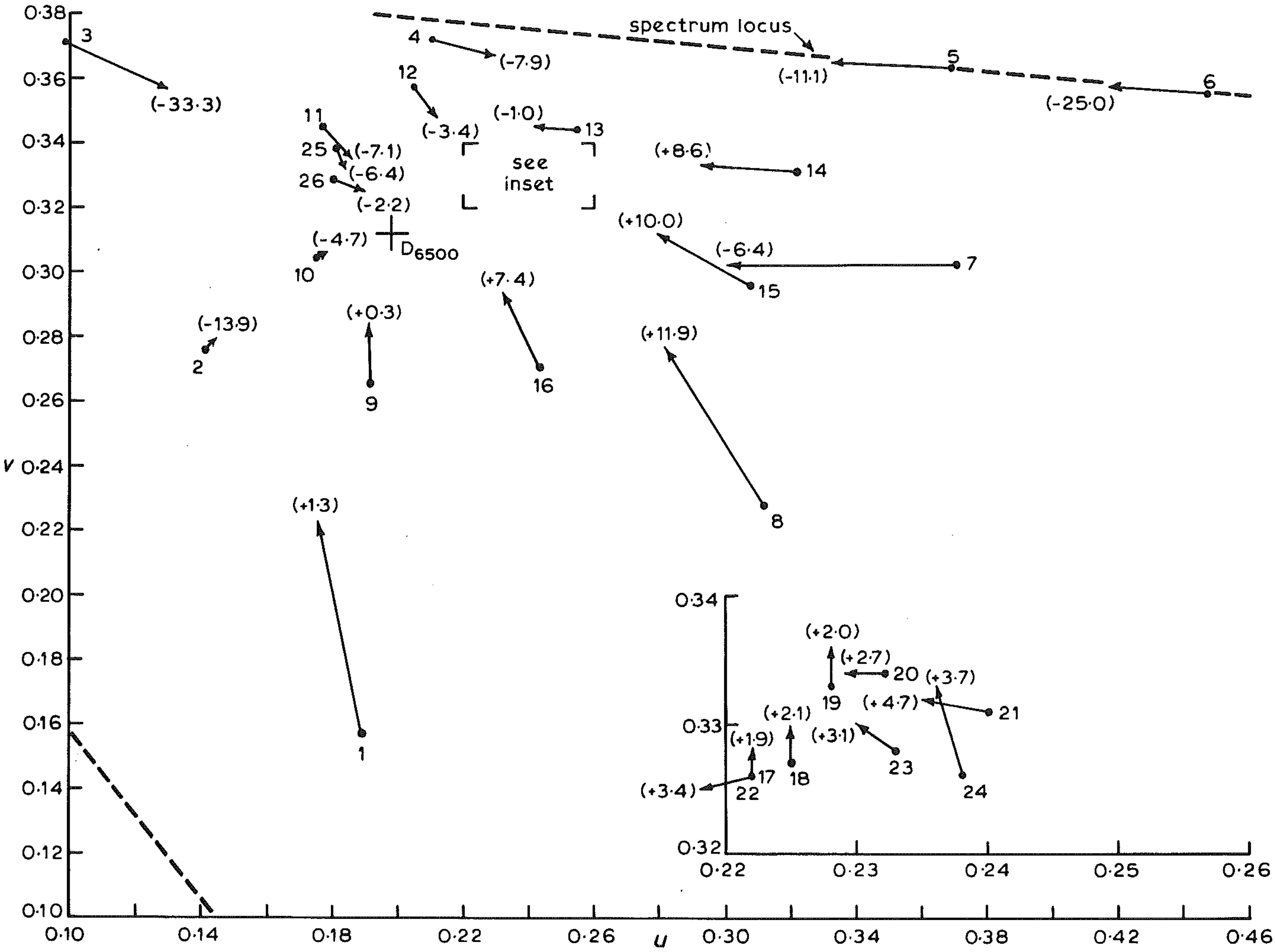


Fig. 8 - Ideal and practical chromaticities and luminance errors for projected colours with D_{6500} as projection illuminant

Figure in brackets is the luminance error in j.n.d. units. Original •——→ Reproduction

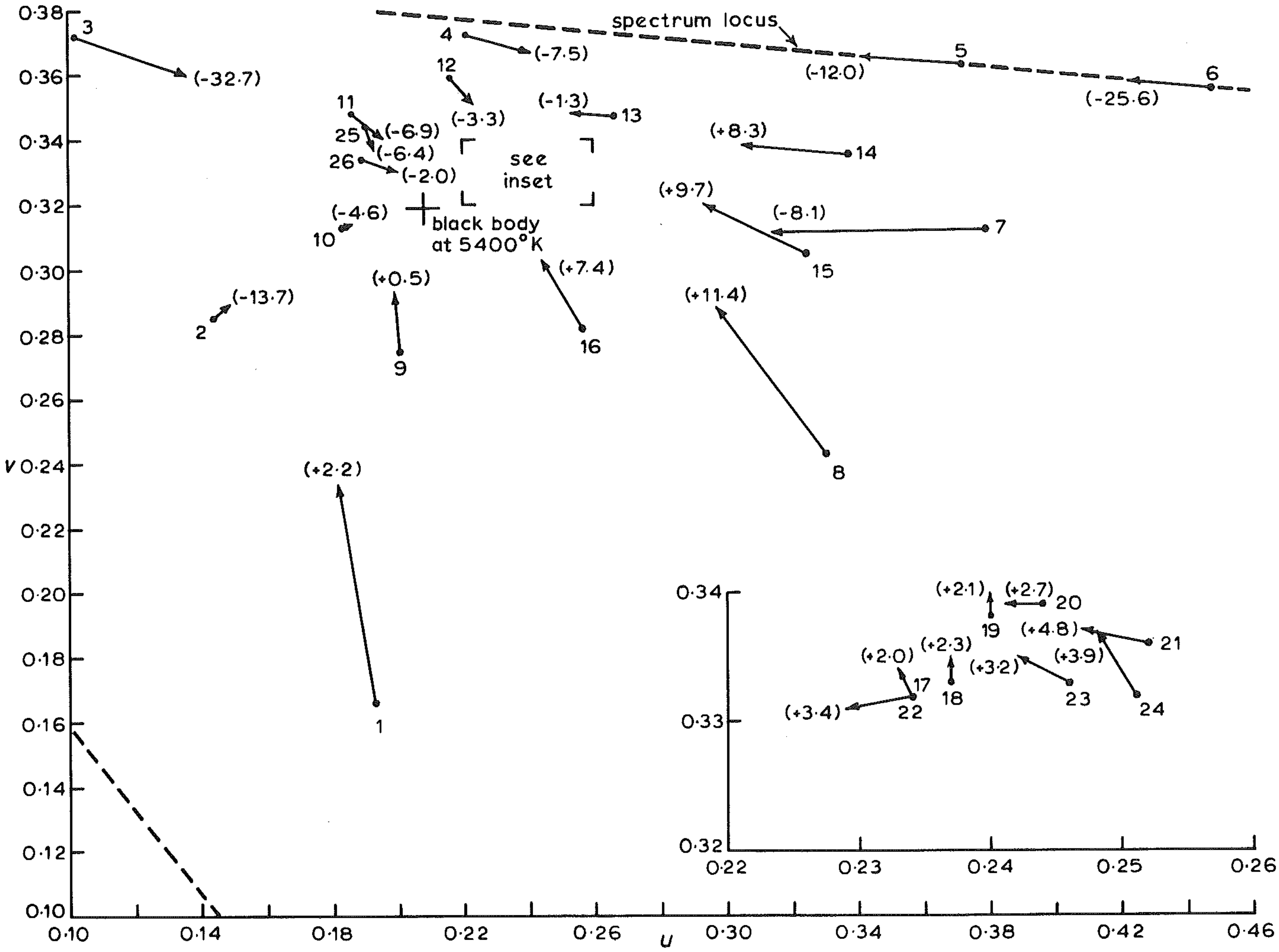


Fig. 9 - Ideal and practical chromaticities and luminance errors for projected colours with 5400°K black-body radiator as projection illuminant

Figure in brackets is the luminance error in j.n.d. units. Original •——▶ Reproduction

TABLE 1

J.N.D. Errors for Various Illuminants

	Mean Chrom.	Mean Lum.	Overall
Illuminant D_{6500} 26 Test Colours	5·2	7·1	8·8
B.B. at 5400°K 26 Test Colours + white	4·9	6·9	8·5
Notched Illuminant D_{6500} 26 Test Colours	3·0	6·5	7·2
Notched B.B. at 5400°K 26 Test Colours + white	2·5	6·3	6·8
3 Gaussian Sources 26 Test Colours + white	2·4	6·4	6·8
Notched B.B. at 5400°K 8 Desaturated Colours + white	1·7	3·3	3·7

B.B. = Black Body (total radiator)

3.3. Illuminant Optimization

The problem of illuminant optimization is essentially the problem of minimizing the errors in the actual display co-ordinates of a set of test colours. In general, an optimum solution found for one set of colours cannot be expected to hold precisely for a different set and the best that can be done is to choose as representative a selection of colours as possible. Further, the optimum solution found on the basis of minimizing, say, the mean chromaticity error does not usually agree with the solution based on minimizing the mean luminance error. In the present investigation a compromise was sought by attempting to minimize the overall error defined in Section 3.2.

A standard computer programme for minimizing an error that is a function of several variables was readily available.[4] It was therefore necessary to specify variables for the projection illuminant upon which the optimization programme could operate.

Since the programme running time was directly dependent on the number of variables it was important to specify the illuminant using the minimum number of parameters.

Elementary consideration indicated that the optimized spectrum could be expected to contain little energy at the wavelengths of the positive dye crossover points, that is at about 480 and 580 nm. This form of spectrum may be realized either by inserting notches in an existing spectrum by means of filters or by synthesizing a spectrum having these properties.

A first attempt was made assuming a synthesized spectrum in the form of three spectral distributions having flat tops and straight sloping sides, the centres of the flat regions being located at the required wavelengths of maximum dye density and the sides near the dye cross-over regions. Although some progress was made, this approach was abandoned because the specification of the illuminant involved 14 variables and a consequently long programme running time; in practice an optimum was never reached. Also the abrupt changes in the spectrum approximation were thought to invalidate the summation approximations of the integrals in equation (6).

The second approach involved a notched spectrum. Each notch was specified in terms of an asymmetrical curve of optical density as a function of wavelength, $d_n(\lambda)$, where

$$d_n(\lambda) = D_n \exp-\left(\frac{\lambda-\lambda_0}{\lambda_1}\right)^2 \quad \text{for } \lambda<\lambda_0$$

and

$$d_n(\lambda) = D_n \exp-\left(\frac{\lambda-\lambda_0}{\lambda_2}\right)^2 \quad \text{for } \lambda>\lambda_0$$

The resulting variables required, for each notch, were therefore two shape factors, (λ_1 and λ_2) the peak absorption (D_n) and the wavelength of peak absorption (λ_0).

The first illuminant investigated was D_{6500}. The initial values of the variables were chosen so that the notches removed most of the illuminant energy at the wavelengths of the dye cross-overs and the programme was run for the 26 test colours. The results for this optimization are shown in Fig. 10 and the corresponding illuminant in Fig. 11. The mean errors are summarized in Table 1 (row 3). It should, however, be noted that in this case only a partial optimization was possible in the restricted programme running time available.

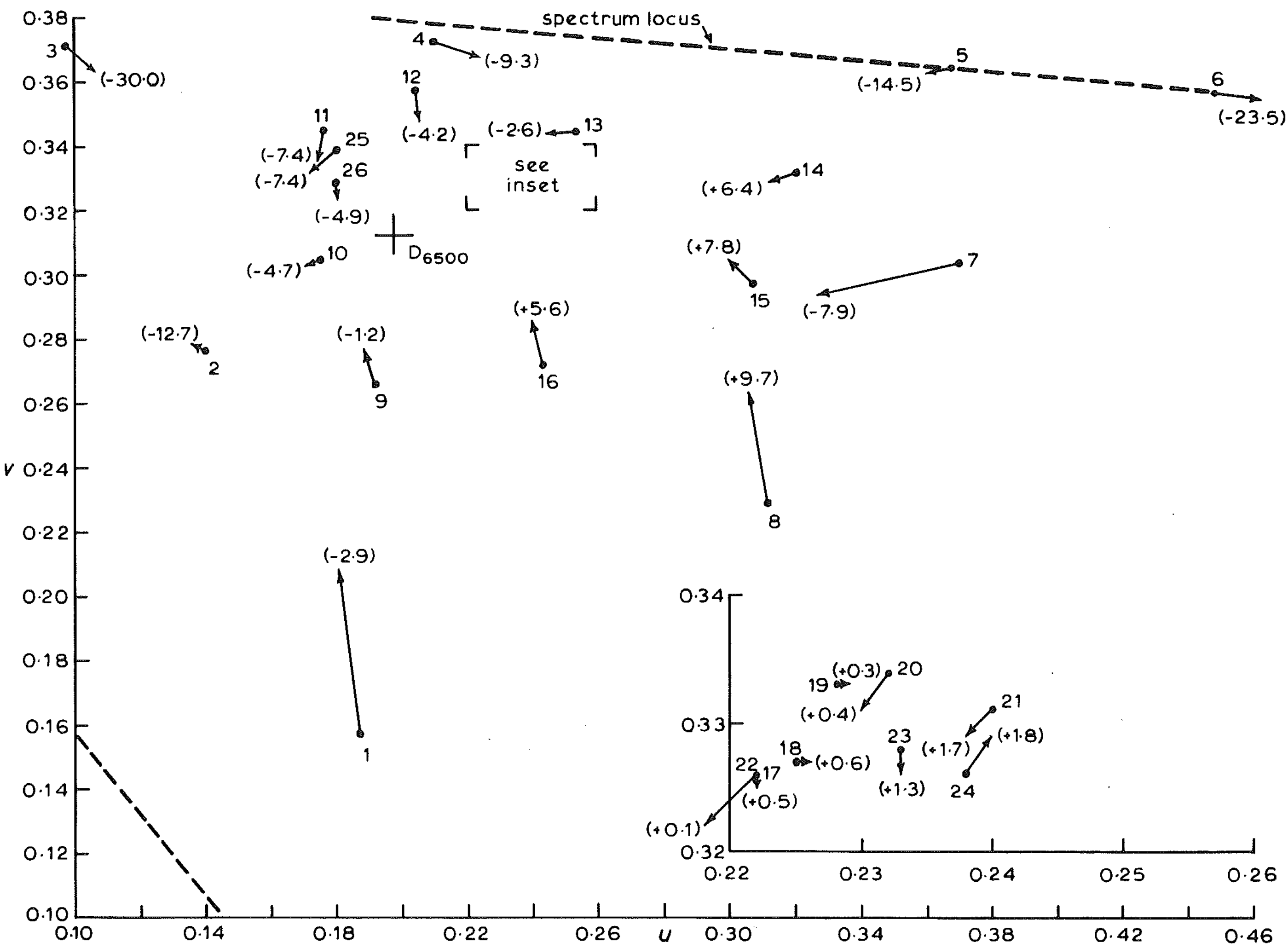


Fig. 10 - Ideal and optimized chromaticities and luminance errors for notched D_{6500} source and 26 test colours

Figure in brackets is the luminance error in j.n.d. units. Original ●——▶ Reproduction

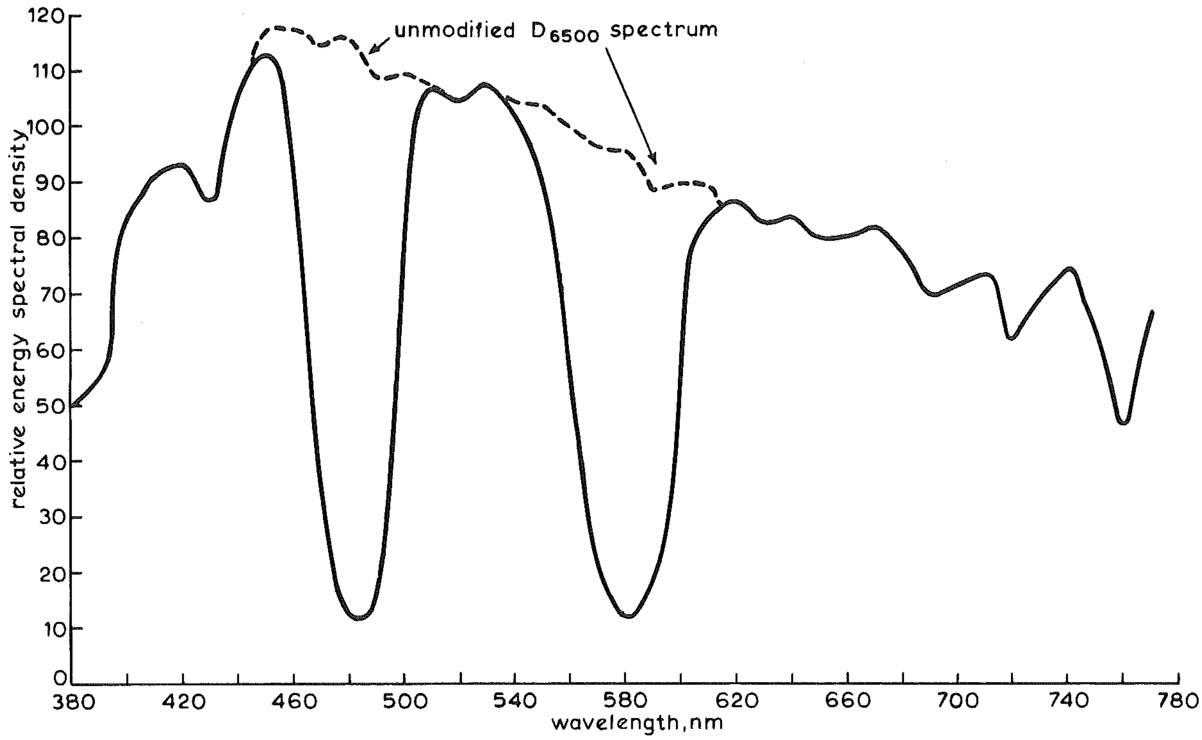


Fig. 11 - Spectrum of optimized notched D_{6500} source, 26 test colour optimization

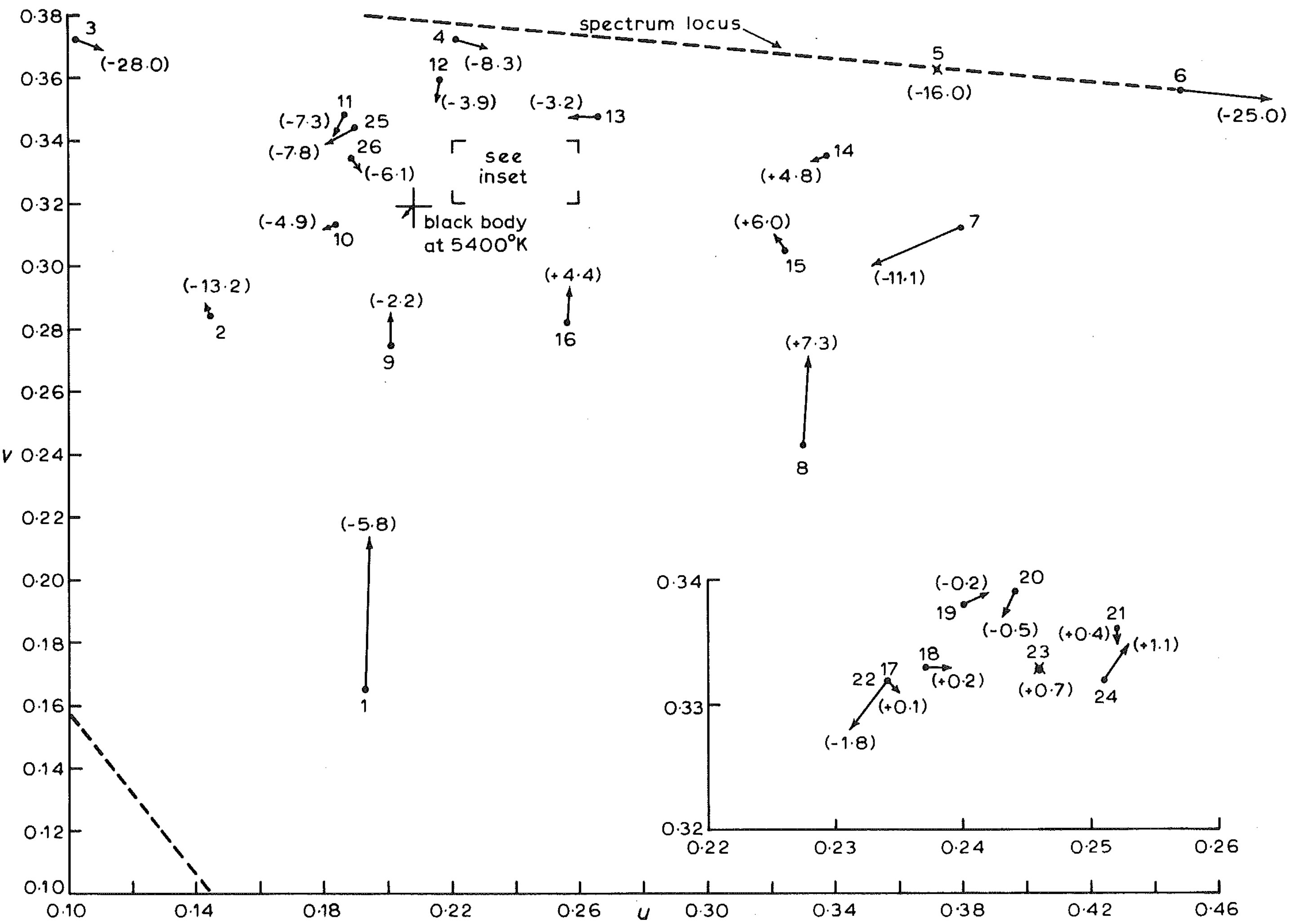


Fig. 12 - Ideal and optimized chromaticities and luminance errors for notched 5400°K source and 26 test colours

Figure in brackets is the luminance error in j.n.d. units. Original ——→ Reproduction

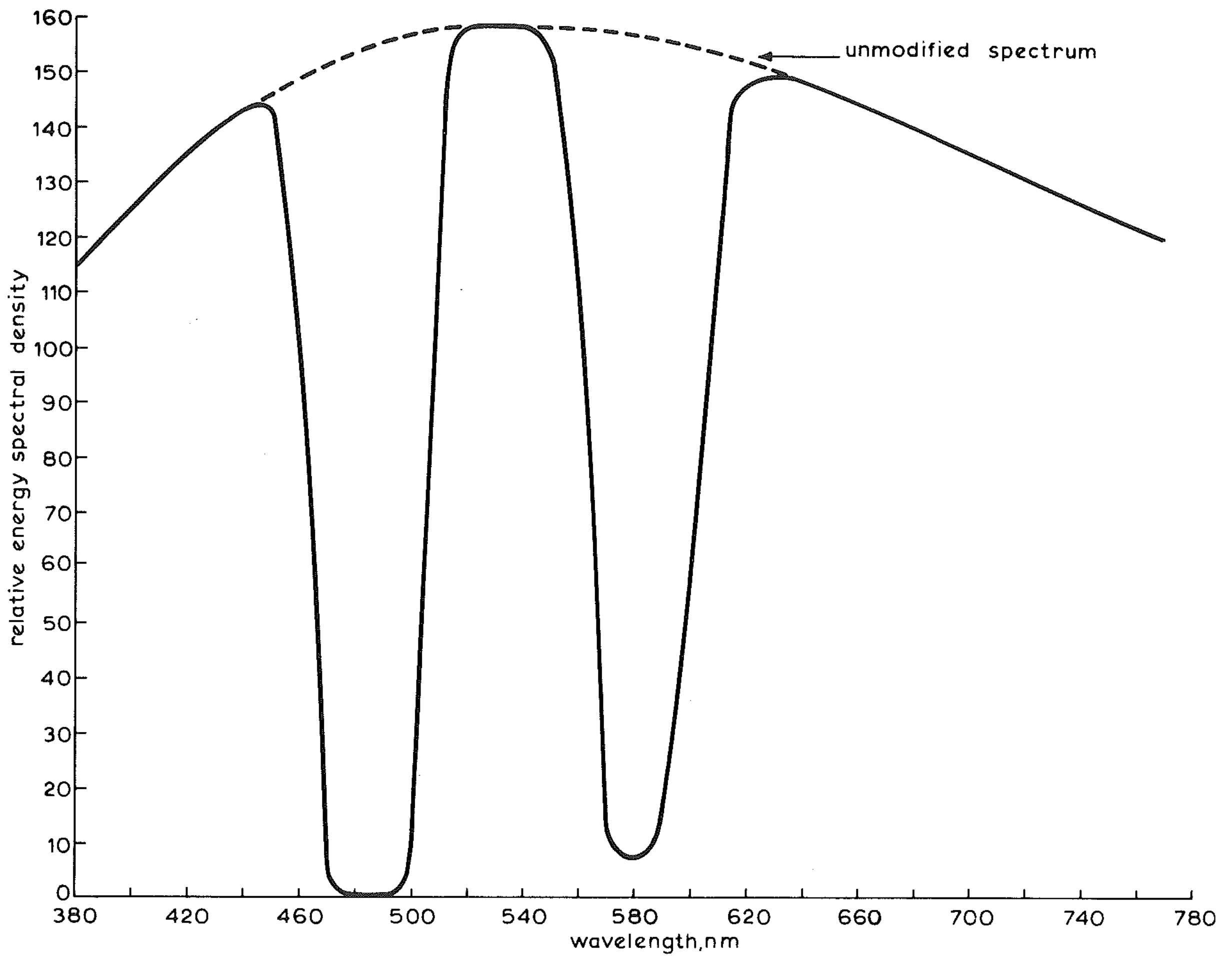


Fig. 13 - Spectrum of optimized notched 5400°K source, 26 test colour optimization

A second illuminant spectrum investigated was that of a black-body radiator at a temperature of 5400°K. It was discovered that the failure to reach an optimum in the case of the test colours and the notched D_{6500} source was caused by an inappropriate choice of step size for each variable in the optimization. With a more appropriate choice the optimization ran satisfactorily to completion. The programme was run for the 26 test colours and white. The displayed co-ordinates and errors are shown in Fig. 12 and the corresponding illuminant in Fig. 13. The mean errors are summarized in the fourth row of Table 1.

As a check on the validity of these solutions for the 5400°K source, the approach of illuminant spectrum synthesis was again tried in the form of a combination of three sources of gaussian spectral distribution. Eight variables were again required for complete specification of the sources; these were three peak wavelengths, three shape factors and two factors relating the blue and red source peak intensities to that of the green. The initial values of the variables were chosen so that the source peak wavelengths coincided with the wavelengths of the peaks of the respective dye density curves. The ideal display co-ordinates were calculated with respect to a black-body source at 5400°K, as before, and a near metameric match to the black-body spectrum was obtained by including white as a test colour. The display co-ordinates and errors are shown in Fig. 14 and the optimized spectrum in Fig. 15. The average errors are given in Table 1 (row 5) and it will be seen that the results are almost identical with the notched source case (see Fig. 12).

The effect of the choice of test colours included for the optimization process was investigated by repeating the case of the illuminant corresponding to a black-body radiator at a temperature of 5400°K, but using only the eight desaturated colours (nos. 9 to 16) and white instead of the complete set of 26 colours and white. The resulting display co-ordinates and errors are shown in Fig. 16 and the corresponding spectrum in Fig. 17, while the mean errors are given in the bottom row of Table 1. It can be seen that much wider notches are produced in the basic spectrum when using only the desaturated colours than when using the full set of colours. Conversely, a further optimization process using only saturated colours (Nos. 1 to 8) and white produced much narrower notches than when using the full set of colours. These two cases are, however, less representative of practical conditions than the use of the full set of test colours.

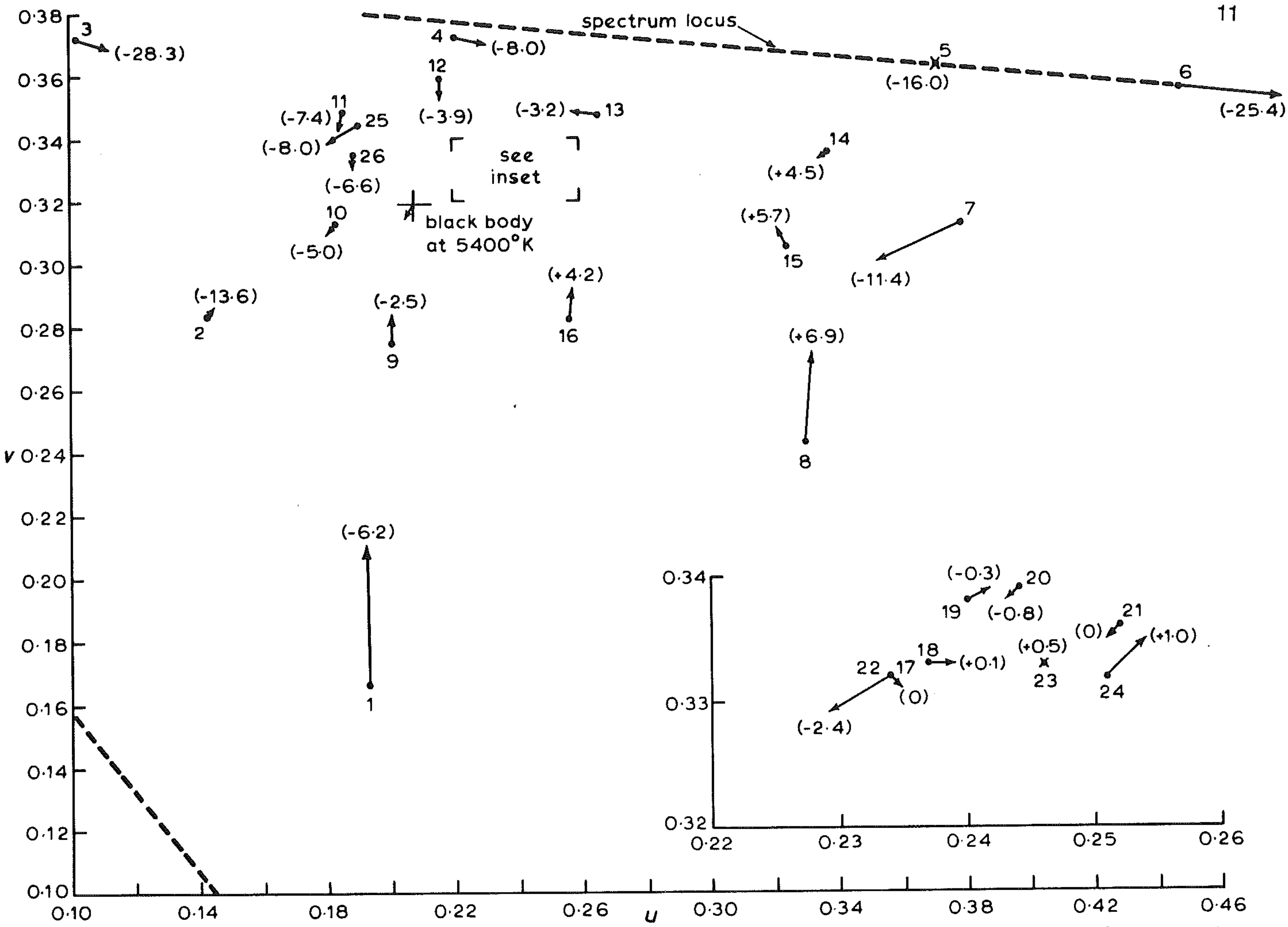


Fig. 14 - Ideal and optimized chromaticities and luminance errors for triple gaussian source and 26 test colours

Figure in brackets is the luminance error in j.n.d. units. Original ——→ Reproduction

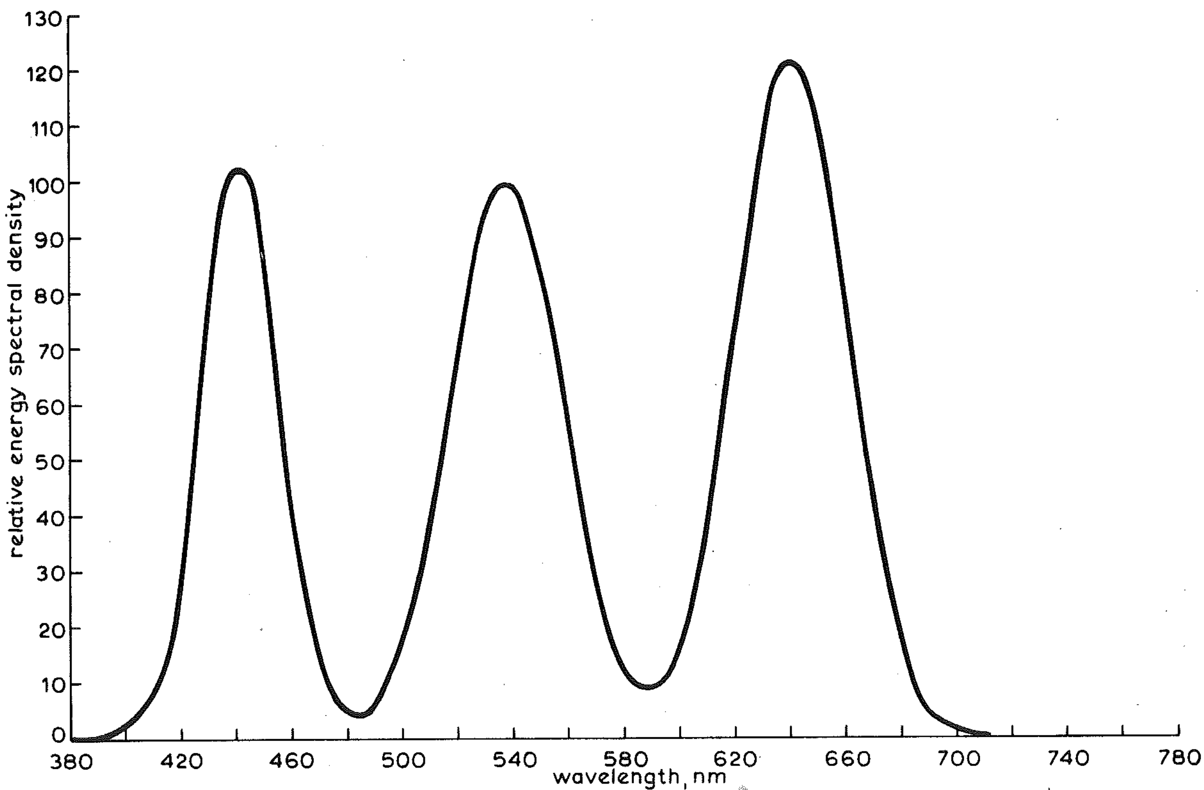


Fig. 15 - Spectrum of optimized triple gaussian source, 26 test colour optimization

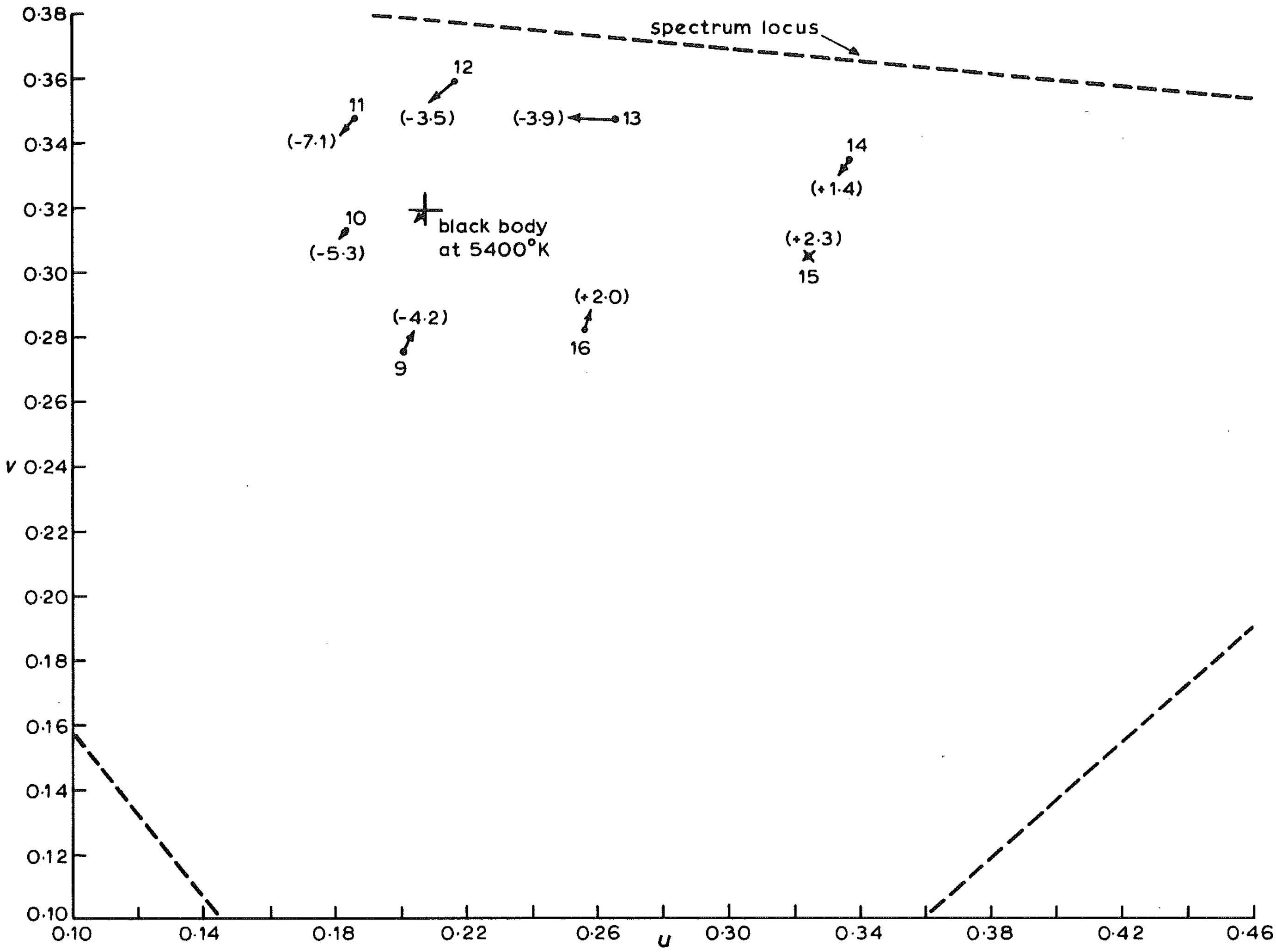


Fig. 16 - Ideal and optimized chromaticities and luminance errors for notched 5400°K source and 8 desaturated colours

Figure in brackets is the luminance error in j.n.d. units. Original → Reproduction

4. DISCUSSION

The results of the optimizations indicate worthwhile improvements in the chromaticity of the displayed colours. Figs. 9 and 12 are particularly relevant. The most noticeable improvements occur with the saturated colours 3, 5, 7 and 8. The reason for this can be appreciated by considering the film spectral transmission and object reflectance curves of Figs. 2 to 7. The removal of illuminant energy in narrow bands centred on 480 and 580 nm corresponds to a sharpening of the peak for colour 3 and this increases its effective saturation. Likewise, with colour 7 the sides of the trough in the curve are sharpened up. The explanation for colour 5 is somewhat different. Because the red end of the spectrum locus in the chromaticity diagram is virtually a straight line, any spectrum which contains energy confined only to wavelengths above 560 nm represents a saturated colour. The reflectance spectra for colours 5 and 6 both satisfy this condition and so, almost, do the respective film positive-transmission spectra. The removal of energy at about 580 nm serves, therefore, only to alter the dominant wavelength of the reproduced colour and move it along the spectrum locus. In the case of colour 6 this process overcorrects the error.

Large improvements are also noted in the desaturated colours 14 and 15 which lie in the pink-magenta region. Again, reference to the positive-film transmission curve for colour 14 shows that the removal of energy at 580 nm balances the excessive transmission in this region.

The reductions in chromaticity error are, however, offset by an increase in the luminance error for most colours except skin tones. The relative luminance of practically all reproduced colours is reduced by introducing the notches. The only major exception to this is colour 3 most of whose visually effective energy does not occur in the regions near 480 and 580 nm. The decrease in relative luminance only reduces the luminance error for those colours which

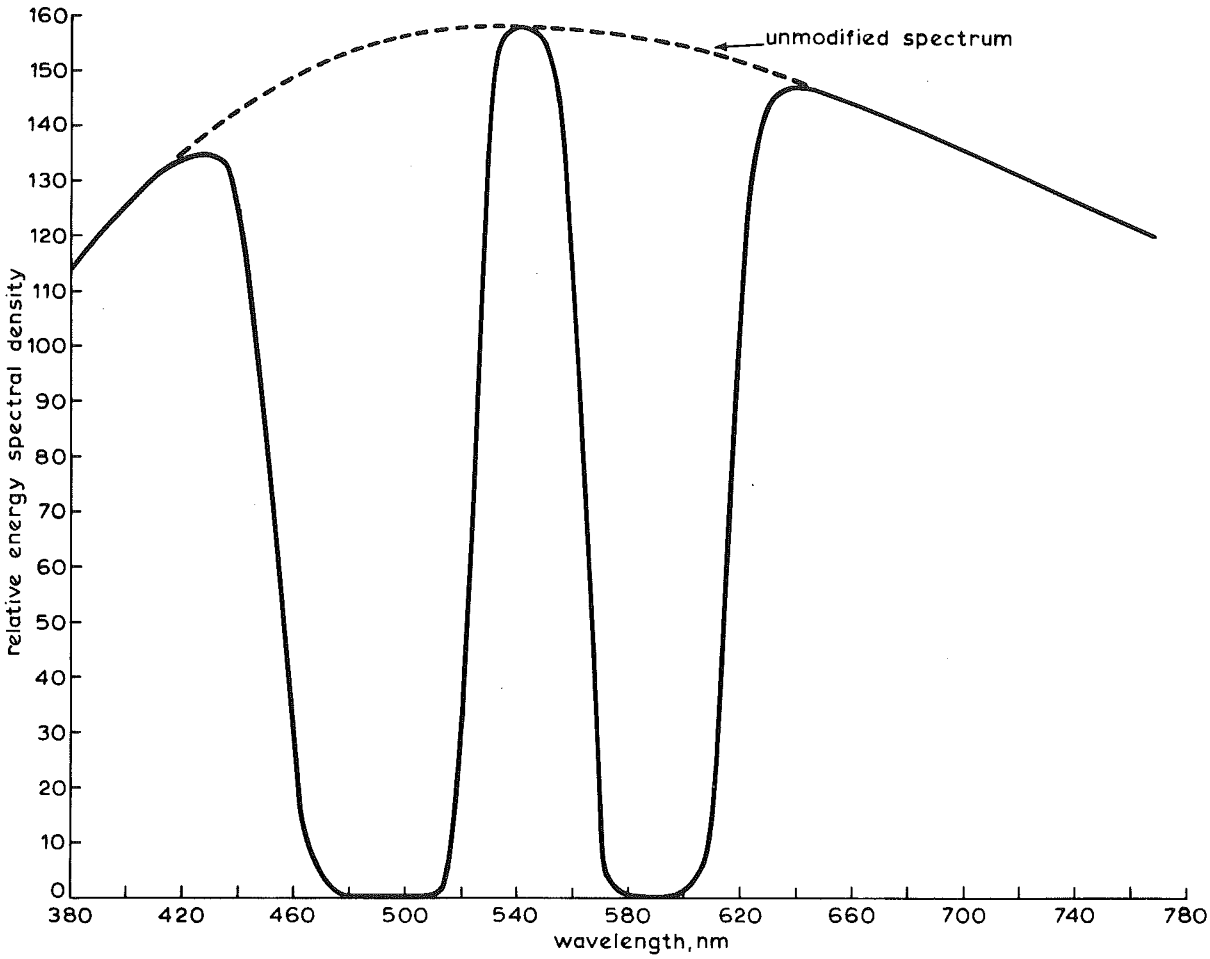


Fig. 17 - Spectrum of optimized notched 5400°K source, 8 desaturated colour optimization

have a large positive error for the unmodified spectrum, that is the colours, 8, 14 and 15 and the skin tones in the pink-magenta region. In the case of colour 1 the reduction overcorrects the error.

5. CONCLUSION

In viewing films by optical projection, the removal of energy at 480 and 580 nm in the spectrum of the projection illumination gives a small reduction in the overall error calculated for a set of 26 test colours. This improvement is composed of opposing factors; a large reduction in mean chromaticity error is accompanied by a small reduction in mean luminance error. The improvement in saturated colours contributes most to the reduction in mean chromaticity error, whereas the reduction in luminance error of skin tones is just sufficient to outweigh the increase in luminance error of the remaining colours to produce a net reduction in mean luminance error.

6. REFERENCES

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